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RESEARCH ARTICLE

Valuating productivity and energy use efficiency in mechanized sesame cultivation

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Abstract

A field investigation at the regional research station in Vriddhachalam, Tamil Nadu, during summer and Kharif 2023 and in the summer of 2024 assessed crop establishment techniques, weed management and harvesting methods on sesame yield and energy efficiency. The main plot treatments included an inclined plate planter with pelletized seeds (M_1), a pneumatic precision planter with pelletized seeds (M_2), a pneumatic precision planter without pelletized seeds (M_3) and manual line sowing (M_4). Subplot treatments comprised Quizalofop ethyl + reaper binder (S_1), Quizalofop ethyl + manual harvest (S_2), hand weeding + reaper binder (S_3) and hand weeding + manual harvest (S_4) in a split-plot design. Line-sown sesame consistently produced higher seed (811, 768, 883 kg/ha) and biological yields (3436, 2979, 3869 kg/ha) along with improved energy parameters, including energy ratio (1.696, 1.617, 1.828), net gain energy and energy productivity across three seasons. Pneumatic precision planters without pelletized seeds showed higher specific energy and energy intensity, while inclined plate planters with pelletized seeds recorded greater economic energy intensity. Among subplot treatments, hand weeding with reaper binder or manual harvest (S_3, S_4) resulted in superior seed and biological yields, lower energy input, higher energy output and better energy productivity. However, Quizalofop ethyl + manual harvest (S_2) exhibited increased specific energy and economic energy intensity. This study highlights the benefits of sustainable practices and energy-efficient mechanization in sesame cultivation. The combination of line sowing, manual weed control and mechanized harvesting optimizes energy use and enhances productivity, supporting eco-friendly and economically viable sesame farming.

Keywords

energetics; efficiency; energy input; energy output; mechanization; sesame; yield

Introduction

Sesame (*Sesamum indicum* L.) is a vital oilseed crop renowned for its rich nutritional profile and high oil content. This ancient crop, cultivated for thousands of years, is highly valued for its stability, drought tolerance and ease of oil extraction. Often referred to as the 'Queen of Oilseeds' due to its excellent shelf life and strong resistance to oxidation and rancidity (1,2), sesame boasts the highest oil content among oilseeds, ranging from 46 to 64% and contains 25% protein (3,4). Globally, sesame is predominantly cultivated in tropical and subtropical regions, with Asia and Africa collectively producing over 93% of the world's sesame supply. In India, major sesame-producing states include Gujarat, Madhya Pradesh, Rajasthan, Uttar Pradesh, Odisha, Maharashtra, Tamil Nadu, Andhra Pradesh and West Bengal. Despite its global significance, India's sesame yield remains relatively low, averaging 391 kg/ha significantly below yields achieved in other parts of the world (5). A major factor contributing to this productivity gap is the reliance on labour-intensive traditional farming methods, which are increasingly challenged by labour shortages and untimely agronomic practices. Across the globe, the adoption of mechanized farming has proven transformative in enhancing the productivity of oilseed crops. Mechanization not only reduces labour dependency but also optimizes resource use and ensures timely operations. Incorporating global advancements in agricultural mechanization into India's sesame cultivation practices could bridge the yield gap, improve economic returns and position the crop as a sustainable and competitive agricultural product.

Mechanization significantly accelerates agricultural operations and enhances crop yields (6). The adoption of mechanized farming practices offers numerous advantages over traditional cultivation methods, including higher efficiency, reduced labour dependency and improved safety. Mechanized sowing, using tools like precision seed drills or seeders, enables timely planting, precise seed placement and optimal spacing, which contribute to uniform germination and increased yields. Weed management, a critical factor in crop production, benefits from herbicide application, which reduces competition for light, moisture and nutrients while boosting yields. Pre-emergence herbicides target early weed growth, while post-emergence applications address weeds that emerge later (7). In crops such as sesame, which are prone to dehiscence upon maturity, delays in harvesting due to labour shortages can lead to over-maturity and significant yield losses. Mechanized harvesting mitigates this issue, ensuring timely operations, reducing yield losses and minimizing physical exertion for farmers while enhancing economic returns (8). Despite these advantages, the adoption of mechanized practices in sesame cultivation remains limited due to concerns about economic feasibility and energy efficiency compared to traditional methods like manual sowing and weeding. As modern agriculture increasingly prioritizes sustainability, understanding the energy dynamics of farming systems has become essential. Energy inputs in agriculture come in various forms human labour, machinery, fuel, agrochemicals and electricity and are categorized as direct (fuel, labour) or indirect (seeds, machinery) and either renewable (labour, seeds) or non-renewable (fuel, agrochemicals) (9). Energy input-output analysis evaluates agricultural efficiency using metrics such as energy productivity, energy use efficiency and net energy. Such analyses provide critical insights into optimizing resource use, enhancing productivity and minimizing unnecessary energy consumption.

While energy use in various crop production systems has been extensively studied (10,11), little to no research has focused on the energy dynamics of mechanized sesame cultivation. This study addresses this significant gap by comprehensively evaluating the energetic inputs, outputs and efficiencies of mechanized sesame farming. What sets this research apart is its systematic comparison of different crop establishment methods, weed management strategies and harvesting techniques with a focus on their energy efficiency. This study not only highlights the potential of mechanization to improve energy use efficiency but also provides a pathway for developing sustainable, resource-efficient practices in sesame cultivation.

Materials and Methods

Experimental site

The field investigation was conducted at the regional research station in Vriddhachalam, Tamil Nadu, India, during summer 2023 (March to May), kharif 2023 (June to September) and summer 2024 (February to May) crop-growing seasons. The research location is situated at a latitude of 11°30'N and a longitude of 79°26'E, with an altitude of 46.7 m above mean sea level. Summarized weather data in Fig. 1 indicated that rainfall was significantly greater during Kharif 2023 than in summer. Other weather conditions were suitable for sesame production, with minimal seasonal variations.

Pre-experimental soil samples collected over the three seasons showed a neutral pH (7.5-7.6) and non-saline status, with electrical conductivity ranging from 0.96 to 1.18 dS/m. The soil contained low available nitrogen (157.2-179.5 kg/ha), moderately available phosphorus (14.3-17.3 kg/ha) and high available potassium (185.3-201.3 kg/ha).

Treatment details and experimental setup

The field trial was set up using a split-plot design with four main plot (M) treatments and four subplot (S) treatments, each replicated three times. The treatment details are given below in Table 1. Furthermore, all plots were applied with a pre-emergence herbicide, Pendimethalin at 0.75 kg a.i./ha, applied three days after sowing of sesame.

Agronomic practices

The sesame variety selected for the field study was VRI 4, which has a field duration of 85-90 days. VRI 4 was chosen for its adaptability, high yield potential and suitability for the study region's agro-climatic conditions. This variety is widely cultivated due to its relatively short duration, making it ideal for evaluating the impact of mechanization and weed management strategies within a defined timeframe. To prevent seed-borne diseases, high-quality sesame seeds were treated with *Trichoderma viride* at 4 g/kg of seed. Seed pelleting was performed using the TNAU seed pelleting mix, to achieve a uniform seed size suitable for precision planting with seed drills. All treatments received farmyard

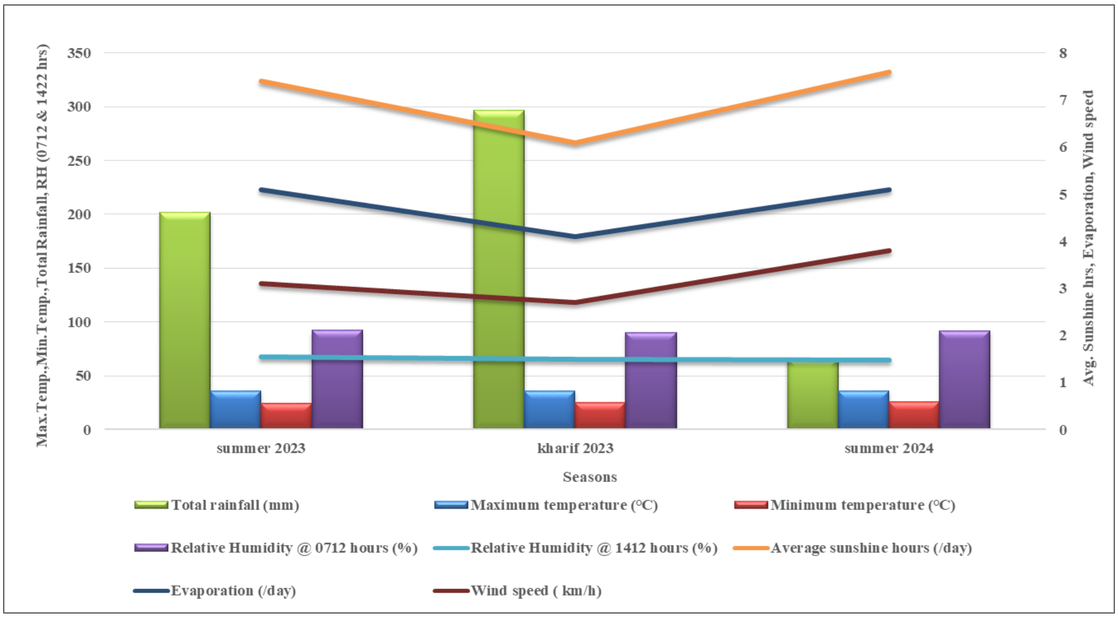


Fig 1. Weather prevailed during the cropping seasons.

Table 1. Treatment details

	Main plots
M_1	Inclined plate planter using pelletized seeds
M_2	Pneumatic precision planter using pelletized seeds
M_3	Pneumatic precision planter using non-pelletized seeds
M_4	Manual line sowing
	Subplots
S_1	Quizalofop ethyl @ 50 g a.i./ha at 20 DAS + reaper binder for harvest
S_2	Quizalofop ethyl @ 50 g a.i./ha at 20 DAS + manual harvesting
S_3	Hand weeding at 30 DAS + reaper binder for harvest
S_4	Hand weeding at 30 DAS + manual harvest

manure (FYM) at 12.5 t/ha. Additionally, a uniform fertilizer application of 35:23:23 kg/ha of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) was provided. The fertilizers used were urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O).

Nitrogen was applied in two phases: half of the nitrogen dose, along with the full amounts of phosphorus and potassium, was incorporated into the soil before sowing as a basal application, while the remaining nitrogen was top-dressed 30 days after sowing. Irrigation was provided as needed during the growing season.

Weed management practices, including manual weeding and herbicide application, were made according to the treatment protocols. The application of Pendimethalin @ 0.75 kg a.i./ha three days after sowing was common to all plots. To manage pest issues, especially vectors of sesame phyllody, a foliar spray of Imidacloprid (0.2 mL/L of water) was applied at 45 DAS, followed by Thiamethoxam (0.2 g/L of water) at 60 DAS. Harvesting methods varied by treatment and included traditional manual harvesting and mechanical harvesting using a reaper binder.

Yield analysis

All the plants from the designated net plot area for each treatment were harvested, sun-dried, threshed, cleaned and weighed to determine seed yield (kg/ha). The above-ground biomass (excluding capsules) from the same plot area was also collected, sun-dried and weighed to determine stalk yield (kg/ha). By adding seed and stalk yields, the biological yield (kg/ha) arrived.

Cost of cultivation

The cost of cultivation was computed based on the input and machinery used.

Energy use efficiency (EUE) or Energy ratio**:** The EUE or energy ratio is the ratio of energy output to the energy input *i.e.,* how much energy was produced for every unit of energy consumed (12). The energy ratio is determined by the following equation,

Energy input (Ei) = Ehl + Emp + Es + Ef + Ep

Where,

Ehl -Energy from human labour,

Emp -Energy from machinery power

Es -Energy from seed,

Ef -Energy from fertilizer and

Ep-Energy from pesticides.

Energy output (Eo) = Ey

Where,

E_y – Energy from seed yield.

$$\text{Energy ratio}= \frac{\text{Energy Output (MJ/hA)}}{\text{Energy input (MJ/hA)}}$$

Specific energy

The quantity of energy required to produce a unit of crop yield is referred to as specific energy. It is indirectly proportional to energy use efficiency *i.e.,* increased specific energy indicates lower energy use efficiency. It is calculated by the using following formula.

$$\text{Specific energy (MJ/ha)}= \frac{\text{Energy input (MJ/ha))}}{\text{Yield (kg/ha)}}$$

Net energy returns

The difference between the energy produced and energy consumed i.e., energy output and energy input is the net gain energy. It is determined by the formula given below.

$$\text{Net energy returns (MJ/ha)} = \text{Energy output (MJ/ha)} - \text{Energy input (MJ/ha)}$$

Energy balance/unit input

Energy balance/unit input was calculated by system net energy returns divided by total system energy inputs.

$$\text{Energy balance/unit input} = \frac{\text{Net energy returns (MJ/ha)}}{\text{Total energy input (MJ/ha)}}$$

Energy productivity

Energy productivity gives quantitative information on how much crop is produced per unit of input energy.

$$\text{Energy productivity (kg/MJ} = \frac{\text{Yield (kg/ha)}}{\text{Energy input (MJ/ha)}}$$

Energy intensiveness

Energy intensiveness is calculated by the total energy input divided by the cost of cultivation.

$$\text{Energy intensiveness (MJ/₹)} = \frac{\text{Total energy input (MJ/ha)}}{\text{Cost of cultivations (₹)}}$$

Energy intensity in physical term

Energy intensity in physical terms is calculated by the total energy input divided by the biological yield.

$$\text{Energy intensity in physical term (MJ kg)} = \frac{\text{Energy input (MJ/ha)}}{\text{Biological yield (kg/ha)}}$$

Energy intensity in economic term

Energy intensity in economic terms is calculated by total energy input divided by the biological yield.

$$\text{Energy intensity in economic terms (MJ kg)} = \frac{\text{Energy output (MJ/ha)}}{\text{Cost of cultivation(₹/ha)}}$$

Derivation and Validation of Energy Equivalents

Energy equivalents for inputs such as labour, machinery and herbicides were derived using established literature values from prior studies and standard conversion factors. For human labour, energy equivalents were calculated based on the average caloric expenditure per hour of agricultural work, as documented in energy balance studies. Machinery energy was estimated by factoring in fuel consumption rates, operating hours and the energy content of diesel. For seeds, fertilizers and herbicides, the energy equivalents were sourced from life cycle assessments and databases of input production and validated through comparisons with values reported in similar agro-energy studies. To ensure accuracy, these energy equivalents were cross-verified with data from agricultural research institutions and aligned with methodologies widely accepted in energy use studies for other crops. This robust approach ensures that the calculated energy inputs and outputs accurately reflect real-world conditions in sesame cultivation. The energy equivalents of the inputs and outputs are presented in Table 2.

Table 2. Energy equivalents for various components of crop production

Source	Unit	Energy equivalent (MJ/ha)	References
A. Inputs			
1. Seeds	kg	15.2	(13)
2. Labour			
Human labour	H	1.96	(14)
3. Machinery			
Electric motor	kg	64.80	(14)
Tractor	kg	62.70	(14)
4. Fuel			
Diesel	L	56.31	(15)
Petroleum	L	46.3	(15)
Electricity	kWh	11.93	(15)
5. Fertilizers			
Nitrogen	kg	60.6	(13)
Phosphorus	kg	11.1	(13)
Potassium	kg	6.7	(13)
6. Chemicals			
Insecticide	kg	199	(14)
Fungicide	kg	92	(14)
Herbicides	kg	238	(14)
Water	kg	1.02	(16)
FYM	kg	0.3	(17)
B. Outputs			
1. Sesame seed	kg	25.0	(18)

Statistical analysis

The collected data were subjected to statistical analysis (14) by using AGRES software version 7.0. If the treatment differences were found significant (S), critical differences (CD) were worked out at a 5% probability level. Treatment differences that were not significant are denoted

Results and Discussion

Yield

The data of seed yield and biological yield are presented in Table 3. Different crop establishment methods significantly influenced the sesame seed and biological yields. When comparing planting methods, line-sown sesame demonstrated superior results (811 kg/ha), showing increases of 6.90%, 12.94% and 18.86% in seed yield compared to alternative methods *viz.,* inclined plate planter with pelletized seeds (M_1), pneumatic precision planter with pelletized seeds (M_2) and without pelletized seeds (M_3), respectively, during the summer 2023 season. The biological yield of sesame also followed comparable patterns and recorded a significantly higher biological yield of 3436 kg/ha during the summer 2023 season. The trend remained consistent in the following seasons, kharif 2023 and Summer 2024. The superior performance of manual line sowing over mechanized methods can be attributed to several factors, particularly seed placement accuracy and plant vigor. In manual line sowing, seeds are placed at uniform depths and spacings, ensuring optimal

Table 3. Effect of different crop establishment techniques, weed management and harvesting methods on yields of sesame

Treatments	Seed yield (kg/ha)			Biological yield (kg/ha)			Cost of cultivation (₹/ha)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	755	715	824	3198	2758	3621	48362	47262	49432
M_2	706	666	770	2982	2547	3389	49899	49049	50969
M_3	658	619	721	2759	2344	3168	49603	48753	50673
M_4	811	768	883	3436	2979	3869	55687	54837	56757
S. Em. ±	13	12	14	53	49	61	-	-	-
C.D. (P=0.05)	44	41	48	185	170	212	-	-	-
Subplots (S)									
S_1	708	671	778	2984	2550	3422	42983	41883	44053
S_2	684	653	749	2909	2480	3307	47942	47092	49012
S_3	781	736	849	3282	2847	3710	53257	52407	54327
S_4	758	707	820	3201	2751	3606	59369	58519	60439
S. Em. ±	15	14	17	56	58	72	-	-	-
C.D. (P=0.05)	43	41	48	164	169	211	-	-	-

germination and uniform crop establishment. This uniformity fosters robust plant growth and higher yield attributes, including better branching, pod formation and seed filling. Conversely, the reduced seed and biological yields observed in machine-sown sesame, particularly with the pneumatic precision planter without pelletized seeds (M_3), are linked to inconsistent seed placement, leading to uneven germination and suboptimal crop establishment. Additionally, the maximum missing seed index percentage and poor initial vigor in machine-planted fields likely contributed to diminished growth and yield characteristics. Interestingly, mechanical planting of pelletized sesame seeds using a pneumatic precision planter yielded better results than line sowing. The benefits of pelletization, such as improved seed flow and uniform placement, partially offset the limitations of mechanization, as previously reported (19).

The significant impact of various combinations of weed management and harvesting techniques on sesame seed and biological yields over three seasons was also evident. The treatment involving hand weeding at 30 DAS and harvesting with a reaper binder (S_3), which was on par with manual harvesting (S_4), consistently recorded higher seed and biological yields across all three seasons compared to other treatments. During the summer 2023 season, sesame seed yield increases for S_3 over S_1 and S_2 were 9.34% and 12.41%, respectively, while for S_4, they were 6.59% and 9.76%, respectively. The Kharif 2023 and Summer 2024 seasons showed a similar pattern. Biological yield results mirrored this trend, with S_3 and S_4 outperforming S_1 and S_2. This outcome can be attributed to reduced weed density and competition throughout the plant development stages, which enhanced photosynthate accumulation and improved yield parameters, ultimately boosting seed and biological yields. Likewise, previously sesame yield enhancement due to efficient weed management was reported (20). Variables such as seed yield and biological yield showed a positive correlation with each other. This implied that an increase in one of these variables was often associated with a corresponding increase in the other (Fig. 2).

The lowest seed and biological yields were recorded for the treatment with Quizalofop ethyl @ 50 g a.i./ha applied at 20 DAS and manual harvesting (S_2), largely due to suboptimal growth and yield attributes linked to poor weed control of broadleaves and sedges compared to hand weeding. There was past evidence (21) of poor broadleaves and sedges control by the Quizalofop ethyl in sesame cultivation that supports the present results.

The interaction among different crop establishment methods, weed management practices and harvesting techniques on sesame seed and biological yields was found to be non-significant.

Production cost

The cost of cultivation of various treatments showed considerable differences in sesame. Among the different crop establishment techniques, line-sown sesame (M_4) recorded the higher cost of cultivation (₹ 55687/ha, ₹ 54837/ha and ₹ 56757/ha) during summer 2023, kharif 2023 and summer 2024, respectively. More human labour used for sowing operations in this line of sowing sesame treatment resulted in a higher cost of cultivation compared to other treatments. These results align with the past reports wherein, there was an increased cost of cultivation in the line-sown groundnut compared to machine-sown (22). The lowest cost of cultivation was observed when sesame was sown using an inclined plate planter with pelletized seeds (M_1) across all three seasons. The primary reason for the reduced cost of this treatment was the use of machinery for sowing and less involvement of labour. A previous study on sorghum crops involving different mechanized sowings reported a lower cost of cultivation (23) also supports the present study.

With regards to weed management and harvesting methods, hand weeding at 30 DAS of sesame along with the sesame crop harvested manually (S_4) recorded a higher cost of cultivation (₹ 59369/ha, ₹ 58519/ha and ₹60439/ha) during summer 2023, kharif 2023 and summer 2024, respectively. Weeding and harvesting were important labour-intensive operations in sesame production. More number of labourers are involved in these operations leading to a higher cost of cultivation. Similarly, the enhanced cost of cultivation due to the use of manual labours for the weeding of sesame was reported earlier (24) strongly supports the study. Application of Quizalofop ethyl @ 50 g a.i./ha at 20 days after sowing (DAS) followed by harvesting with a reaper binder (S_1) recorded the lower cost of cultivation during all three seasons of study. Herbicides for weed management and machines for harvesting play a vital role in lower production costs in sesame cultivation. The past reports of reduced cost of cultivation due to mechanized cultivation were in line with the current study (25). The cost of cultivation had a significantly positive correlation with energy input (Fig. 2). The changes in one variable influenced the other in a similar pattern.

Across all seasons, no significant interaction was observed between crop establishment techniques and weed management and harvesting methods in terms of sesame cultivation costs.

Energetics

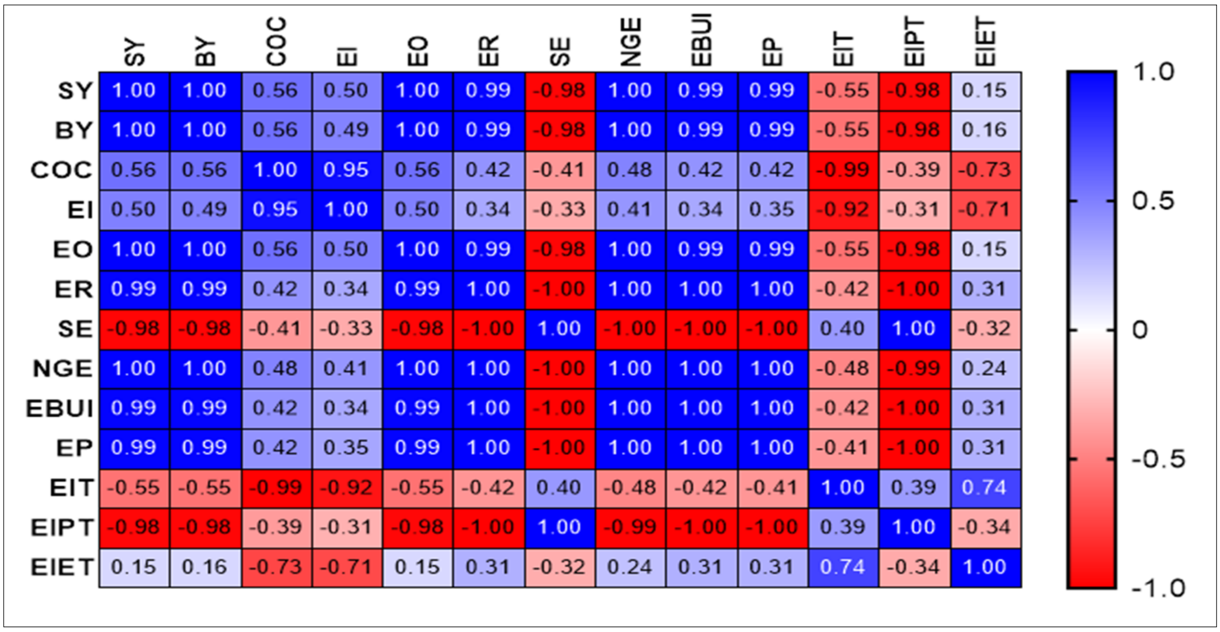
Energy use efficiency

The data to input energy, output energy and energy use efficiency are shown in Table 4. Within the various crop establishment techniques, line-sown sesame (M_4) achieved a higher input energy (11951 MJ/ha) compared to all other three machine-sown treatments during the summer 2023 season. This trend follows for the other two seasons (kharif 2023 and summer 2024). More labour was engaged in sowing sesame in lines, which was the reason for the higher energy input. Whereas, in all other three treatments (M_1, M_2 and M_3), usage of machines for sowing reduced the input energy during summer 2023, kharif 2023 and summer 2024. The energy requirement for sowing was higher in the line sowing method compared to the mechanized method, which also accounted for energy spent on seed treatment, thinning and gap filling. These operations demand more manual labour. A similar report was noted in the findings of Arivazhagan who stated that the usage of machines in groundnut had reduced the input energy (26).

Regarding energy output, line sown sesame significantly achieved the highest values (20275 MJ/ha, 19188 MJ/ha and 22069 MJ/ha during summer 2023, kharif 2023 and summer 2024, respectively). The line-sowing method reflects its superior yield performance due to precise seed placement, uniform crop establishment and improved plant vigor. These factors contribute to better utilization of available resources, leading to enhanced seed and biological yields. Similar trends have been reported in previous studies, where optimal agronomic practices significantly boosted energy outputs in oilseed crops (27). This emphasizes the importance of precise sowing techniques in maximizing energy returns and overall productivity. Lower sesame yield accounted for in the other three treatments (M_1, M_2 and M_3) resulted in lower energy output.

The energy ratio, which indicates the efficiency of energy use in production, showed notable differences among treatments. The higher energy ratio was observed in line-sown sesame, with values of 1.696, 1.617 and 1.828 for the summer 2023, kharif 2023 and summer 2024 seasons, respectively which was on par with inclined plate planter sowing sesame (M_1) and significantly higher than other treatments. Though the energy input and energy output values were more in line-sown sesame, the output energy was much higher which ultimately enhanced the energy ratio. Similar findings have been reported by other studies emphasizing the importance of line sowing for maximizing crop performance and energy utilization (28).

In response to weed management and harvesting methods, the higher energy input (12084 MJ/ha) was recorded by hand weeding at 30 DAS of sesame along with the sesame crop harvested manually (S_4) during the summer of 2023. Comparable patterns were followed in the other two seasons. Hand weeding and manual harvest were the most labourious operations involved in sesame cultivation resulting in higher energy input. Hand weeding demands significant manual effort for the precise removal of weeds, while manual harvesting involves careful handling of the crop, both contributing to increased



	SY	BY	COC	EI	EO	ER	SE	NGE	EBUI	EP	EIT	EIPT	EIET
SY	1.00	1.00	0.56	0.50	1.00	0.99	-0.98	1.00	0.99	0.99	-0.55	-0.98	0.15
BY	1.00	1.00	0.56	0.49	1.00	0.99	-0.98	1.00	0.99	0.99	-0.55	-0.98	0.16
COC	0.56	0.56	1.00	0.95	0.56	0.42	-0.41	0.48	0.42	0.42	-0.99	-0.39	-0.73
EI	0.50	0.49	0.95	1.00	0.50	0.34	-0.33	0.41	0.34	0.35	-0.92	-0.31	-0.71
EO	1.00	1.00	0.56	0.50	1.00	0.99	-0.98	1.00	0.99	0.99	-0.55	-0.98	0.15
ER	0.99	0.99	0.42	0.34	0.99	1.00	-1.00	1.00	1.00	1.00	-0.42	-1.00	0.31
SE	-0.98	-0.98	-0.41	-0.33	-0.98	-1.00	1.00	-1.00	-1.00	-1.00	0.40	1.00	-0.32
NGE	1.00	1.00	0.48	0.41	1.00	1.00	-1.00	1.00	1.00	1.00	-0.48	-0.99	0.24
EBUI	0.99	0.99	0.42	0.34	0.99	1.00	-1.00	1.00	1.00	1.00	-0.42	-1.00	0.31
EP	0.99	0.99	0.42	0.35	0.99	1.00	-1.00	1.00	1.00	1.00	-0.41	-1.00	0.31
EIT	-0.55	-0.55	-0.99	-0.92	-0.55	-0.42	0.40	-0.48	-0.42	-0.41	1.00	0.39	0.74
EIPT	-0.98	-0.98	-0.39	-0.31	-0.98	-1.00	1.00	-0.99	-1.00	-1.00	0.39	1.00	-0.34
EIET	0.15	0.16	-0.73	-0.71	0.15	0.31	-0.32	0.24	0.31	0.31	0.74	-0.34	1.00

Fig. 2. Interpretation of Pearson Correlation Analysis of variables along with correlation matrix and heatmap.

SY - seed yield, BY - biological yield, COC - cost of cultivation, EI - energy input, EO - energy output, ER - energy ratio, SE - specific energy, NGE - net gain energy, EBUI - energy balance unit input-1, EP - energy productivity, EIT - Energy intensiveness, EIPT - energy intensity in physical terms, EIET - energy intensity in economic terms.

Table 4. Effect of different crop establishment techniques, weed management and harvesting methods on energy use efficiency of sesame

Treatments	Energy input (MJ/ha)			Energy output (MJ/ha)			Energy ratio		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	11746	11658	11863	18869	17869	20588	1.606	1.532	1.735
M_2	11877	11789	11994	17644	16656	19256	1.486	1.413	1.606
M_3	11854	11766	11971	16450	15463	18025	1.387	1.314	1.505
M_4	11951	11863	12068	20275	19188	22069	1.696	1.617	1.828
S. Em. ±	-	-	-	319	301	348	0.027	0.026	0.029
C.D. (P=0.05)	-	-	-	1103	1042	1205	0.093	0.089	0.101
Subplots (S)									
S_1	11667	11579	11784	17688	16763	19456	1.516	1.448	1.651
S_2	11702	11614	11819	17088	16325	18737	1.461	1.407	1.587
S_3	11975	11887	12092	19525	18406	21237	1.629	1.547	1.755
S_4	12084	11996	12201	18938	17681	20506	1.567	1.474	1.681
S. Em. ±	-	-	-	375	355	413	0.032	0.030	0.034
C.D. (P=0.05)	-	-	-	1095	1036	1205	0.092	0.088	0.101

Interaction absent

Main plot: M_1 - Inclined plate planter using pelletized seeds

M_2 - Pneumatic precision planter using pelletized seeds

M_3 - Pneumatic precision planter using non-pelletized seeds

M_4 - Manual line sowing

Subplot: S_1 - Quizalofop ethyl @ 50 g a.i. ha^{-1} at 20 DAS + reaper binder for harvest

S_2 - Quizalofop ethyl @ 50 g a.i. ha^{-1} at 20 DAS + manual harvesting,

S_3 - hand weeding at 30 DAS + reaper binder for harvest

S_3 - hand weeding at 30 DAS + reaper binder for harvest

energy expenditure. However, these practices often lead to better weed control and crop management, enhancing yield and productivity. In contrast, mechanical methods, while less energy-intensive, may not achieve the same level of precision in weed removal or crop handling. Similar findings in prior studies suggest that labour-intensive methods can yield higher productivity at the cost of increased energy input. This highlights the need for balanced strategies that combine efficiency with productivity in agricultural practices. Similarly, enhanced energy input due to more use of labours for sowing and harvesting of soybeans was reported earlier (29) and strongly aligns with the present study. The S_3 treatment (hand weeding at 30 DAS and reaper binder harvesting) recorded the higher energy output (19525 MJ/ha, 18406 MJ/ha and 21237 MJ/ha and energy ratio in all three seasons, with energy ratios of 1.629, 1.536 and 1.772 for summer 2023, kharif 2023 and summer 2024, respectively, which were on par with S_4 (manual harvesting). This indicates that manual weed management combined with mechanized harvesting provided a higher sesame yield resulting in the best energy returns. The results reflect the combined benefits of effective weed management and semi-mechanized harvesting. Hand weeding at 30 DAS effectively minimized weed competition, enhancing resource utilization and crop vigor, while reaper binder harvesting ensured timely and efficient crop collection with reduced labour costs. The performance of S3 was on par with S4 (manual harvesting), indicating that reaper binder harvesting can match the productivity benefits of manual methods with improved energy efficiency. Previous studies corroborate that integrating precise weed control with mechanized harvesting can optimize energy use while maintaining or enhancing yield levels. These findings highlight the potential of semi-mechanized methods like S_3 for sustainable and energy-efficient sesame. The results of previous studies support this study, where hand weeding is responsible for higher energy output in groundnut cultivation (30). In contrast, the treatment S_2 (Quizalofop ethyl application and manual harvesting) had the lowest energy ratio, with values of 1.461, 1.407 and 1.587 across the seasons, due to lower output (sesame yield) stemming from less effective weed management. This outcome is attributable to the lower sesame yield resulting from less effective weed management. Quizalofop ethyl primarily targets grassy weeds, leaving broadleaf weeds and sedges insufficiently controlled, which increases competition for light, nutrients and water, ultimately reducing crop productivity. Manual hand weeding, by contrast, allows precise and comprehensive weed removal, fostering better crop establishment and higher yields. Studies have consistently shown that suboptimal weed management leads to decreased energy efficiency and yield, as uncontrolled weeds can significantly impact resource availability for the crop. This underscores the importance of integrated weed management approaches for achieving higher energy use efficiency and sustainable crop production. The poor yield of crops reduced the output and energy ratio also reported earlier (23). The trait energy output showed a positive and significant association with the energy ratio. This indicates that a rise in one variable is associated with a proportional increase in the other. The variables energy input and energy input showed a moderate positive correlation. The energy ratio was significantly high positively correlated with energy output and moderately positively correlated with energy input (Fig. 2). About this, the energy ratio aligns closely with the trends observed in energy output.

No interaction effect was observed on the energy use efficiency of sesame in between the combinations of establishment methods, weed management strategies and harvesting techniques across all seasons.

Specific energy

A significant difference in the specific energy of sesame was noted across the various crop planting methods

Table 5. Effect of different crop establishment techniques, weed management and harvesting methods on specific energy, net gain energy and energy balance/unit input of sesame

Treatments	Specific energy (MJ/ha)			Net gain energy (MJ/ha)			Energy balance/unit input		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)									
M_1	15.64	16.38	14.47	7123	6211	8724	0.606	0.532	0.735
M_2	16.96	17.81	15.67	5766	4867	7262	0.486	0.413	0.606
M_3	18.12	19.14	16.70	4596	3697	6054	0.387	0.314	0.505
M_4	14.79	15.50	13.72	8324	7325	10001	0.696	0.617	0.828
S. Em. ±	0.29	0.31	0.27	318	301	348	0.027	0.026	0.029
C.D. (P=0.05)	1.01	1.07	0.95	1103	1042	1205	0.093	0.089	0.101
Subplots (S)									
S_1	16.67	17.45	15.27	6021	5184	7672	0.516	0.448	0.651
S_2	17.30	18.01	15.93	5385	4711	6918	0.461	0.407	0.587
S_3	15.44	16.26	14.34	7550	6519	9145	0.629	0.547	0.755
S_4	16.09	17.11	15.01	6853	5685	8304	0.567	0.474	0.681
S. Em. ±	0.35	0.37	0.32	375	355	412	0.032	0.030	0.034
C.D. (P=0.05)	1.02	1.07	0.94	1094	1036	1205	0.092	0.088	0.101

evaluated (Table 5). Specific energy requirement was significantly maximum (18.12 MJ/ha) with a Pneumatic precision planter without pelletized seeds (M_3) during summer 2023. This high specific energy reflects reduced energy use efficiency, as M_3 requires more energy to produce each unit of sesame seed yield. The absence of pelletized seeds likely led to suboptimal seed placement and establishment, resulting in lower yields and higher energy expenditure per unit output. In contrast, the line-sown sesame (M_4) recorded the lowest specific energy (14.79 MJ/ha), highlighting its superior energy efficiency. Line sowing ensures precise seed placement and better germination, contributing to higher yields and efficient energy utilization. Research supports that precise sowing techniques and optimized seed treatments enhance both crop productivity and energy efficiency by reducing wasteful energy expenditures. These findings emphasize the importance of choosing efficient crop establishment methods for sustainable and energy-efficient farming practices. The outcomes from Kharif 2023 and Summer 2024 displayed comparable patterns. This suggests better energy utilization efficiency, attributed to higher yield potential. These findings align with the results reported by (31), who narrated similarly in sesame. The specific energy demonstrates negative correlations with all other variables (Fig. 2).

For weed management and harvesting methods, the application of Quizalofop ethyl @ 50 g a.i./ha at 20 DAS and manual harvesting (S_2) followed by harvest with reaper binder (S_1) recorded the higher specific energy values of 17.30, 18.01 and 15.93 MJ ha^{-1} during summer 2023, kharif 2023 and summer 2024 seasons, respectively. The higher specific energy values indicate lower energy use efficiency, possibly due to the combined effect of chemical weed management and manual harvesting operations requiring additional energy inputs without proportional yield benefits. The S_3 treatment (hand weeding at 30 DAS and reaper binder harvesting) consistently showed the lowest specific energy values (15.44, 16.26 and 14.34 MJ/ha) across the three seasons. The combination of manual weed management and mechanized harvesting resulted in better energy utilization efficiency. More effective weed control through manual weeding and energy-efficient mechanized harvesting operations, leading to better yield outcomes per unit of energy input. These results align with previous results (32). The specific energy exhibits significant and negative correlation (Fig. 2) with energy ratio, net gain energy, biological yield, energy output and energy productivity. An increase in one of these variables appears to correlate with a decrease in the specific energy value.

There was a non-significant interaction effect on the specific energy of sesame across all seasons when considering the combinations of establishment methods, weed management strategies and harvesting techniques.

Net energy returns and energy balance

The data in Table 5 illustrate the net gain energy and energy balance/unit input for various crop establishment treatments across the summer 2023, kharif 2023 and summer 2024 seasons. The line-sown sesame (M_4) significantly recorded higher net gain energy, with values of 8324 MJ/ha, 7325 MJ/ha and 10001 MJ/ha for summer 2023, kharif 2023 and summer 2024, respectively than other sowing methods. The energy balance/unit input was recorded higher for M_4, with values of 0.696, 0.617 and 0.828 for the respective seasons, which was on par with inclined plate planter sowing sesame (M_1). This indicates that M_4 optimizes energy use for maximum returns, likely due to precise seed placement, better germination and uniform crop establishment. Studies affirm that traditional methods like line sowing, which promote uniform seed distribution and minimal seed loss, lead to better crop growth and yield, ultimately improving energy efficiency. Moreover, the enhanced net energy gains and energy balance/unit input observed in line-sown sesame demonstrate its potential as a sustainable cultivation approach compared to machine-sown alternatives. These findings align with the broader goal of sustainable agriculture by maximizing energy returns while minimizing input-related inefficiencies. These results suggest that line-sown sesame provides better energy output (sesame seed yield) leading to higher energy returns. The advantages of line sowing in improving energy use efficiency were also reported earlier (33) and align with the present results. Pneumatic precision planter without pelletized seeds (M_3) had the lower net gain energy, recording 4596 MJ/ha, 3640 MJ/ha and 6171 MJ/ha and the lower energy balance/unit input at 0.387, 0.314 and 0.505. These lower values reflect the limitations of poor yield of sesame.

The weed management and harvesting methods revealed notable differences in energy metrics. The significantly higher net gain energy values at 7550 MJ/ha, 6519 MJ/ha and 9145 MJ/ha were recorded by hand weeding at 30 DAS and reaper binder harvesting (S_3) during summer 2023, kharif 2023 and summer 2024, respectively over others. The treatment S_3 (hand weeding + reaper binder) was on par with hand weeding + manual harvest (S_4). The energy balance/unit input was significantly higher recorded by hand weeding at 30 DAS and reaper binder harvesting at 0.629, 0.547 and 0.755 for the three seasons which was on par with manual harvest (S_4). The effectiveness of S_3 can be attributed to reduced labour requirements and timely harvesting with the reaper binder, which minimizes yield losses often associated with manual harvesting delays. Studies corroborate that effective weed management boosts photosynthetic efficiency by reducing competition for resources like light, water and nutrients, thereby increasing crop yield and energy output. Furthermore, mechanized harvesting ensures timely operations and reduces physical strain, contributing to higher energy efficiency. These findings highlight the potential of integrating hand weeding and mechanized harvesting to optimize energy returns and promote sustainable sesame cultivation practices. These results highlight the effectiveness of combining manual weed control with mechanized harvesting to enhance energy returns, consistent with earlier findings by (29). Quizalofop ethyl application and manual harvesting showed the lowest net gain energy and energy balance. These results emphasize the limitations of using Quizalofop ethyl as a standalone weed management strategy in sesame cultivation, highlighting the need for integrated weed control practices that address a broader spectrum of weed species. This aligns with findings in other studies that underline the importance of selecting weed control measures tailored to specific crop and field conditions to optimize both yield and energy efficiency. This indicates that less effective weed control methods resulted in reduced energy efficiency, aligning with the previous observations (34). The net gain energy and energy balance/unit input were significantly positively correlated with each other (Fig. 2). Thus, an increase in one variable results in comparable patterns of another variable.

The net gain energy and energy balance/unit input for sesame were not significantly affected by the combined influence of establishment methods, weed management and harvesting practices during any season.

Energy productivity and energy intensiveness

The data presented in Table 6 revealed significant variations in energy productivity and energy intensiveness across different treatments in sesame cultivation over three seasons. Among the crop establishment methods, line sowing (M_4) significantly superior energy productivity of 0.069, 0.064 and 0.074 kg/MJ during summer 2023, kharif 2023 and summer 2024, respectively over others. However, this was on par with the inclined plate planter sowing sesame (M_1). The lower energy productivity was observed in pneumatic precision planters without pelletized seeds (M_3) across the three seasons. Energy productivity is closely linked to sesame seed yield, a decrease in sesame yield leads to a decline in energy productivity. The previous studies (31) reported lower yields responsible for decreasing energy productivity in sesame which supports the current study. The energy productivity was positively correlated with seed yield, energy output and energy ratio (Fig. 2). The increase in seed yield results in the increase of energy productivity.

In the weed management and harvesting techniques, hand weeding at 30 DAS with reaper binder harvesting (S_3) recorded higher energy productivity (0.065, 0.062 and 0.071 kg/MJ) across all three seasons, which was on par with hand

Table 6. Effect of different crop establishment techniques, weed management and harvesting methods on energy productivity and energy intensiveness of sesame

Treatments	Energy productivity (kg/MJ)			Energy intensiveness (MJ/₹)		
	Summer 2023	Kharif 2023	Summer 2024	Summer 2023	Kharif 2023	Summer 2024
Main plots (M)						
M_1	0.064	0.061	0.070	0.2461	0.2506	0.2430
M_2	0.059	0.056	0.065	0.2418	0.2443	0.2389
M_3	0.056	0.052	0.061	0.2417	0.2442	0.2388
M_4	0.069	0.064	0.074	0.2171	0.2189	0.2149
S.Em. ±	0.001	0.001	0.0012	-	-	-
C.D. (P=0.05)	0.004	0.004	0.004	-	-	-
Sub plots (S)						
S_1	0.061	0.058	0.067	0.2722	0.2775	0.2682
S_2	0.056	0.056	0.064	0.2450	0.2476	0.2420
S_3	0.065	0.062	0.071	0.2254	0.2274	0.2231
S_4	0.063	0.059	0.068	0.2040	0.2055	0.2023
S.Em. ±	0.001	0.001	0.001	-	-	-
C.D. (P=0.05)	0.004	0.004	0.004	-	-	-
Interaction absent						

Main plot: M_1 - Inclined plate planter using pelletized seeds
M_2 - Pneumatic precision planter using pelletized seeds
M_3 - Pneumatic precision planter using non-pelletized seeds
M_4 - Manual line sowing

Subplot: S_1 - Quizalofop ethyl @ 50 g a.i. ha^{-1} at 20 DAS + reaper binder for harvest
S_2 - Quizalofop ethyl @ 50 g a.i. ha^{-1} at 20 DAS + manual harvesting,
S_3 - hand weeding at 30 DAS + reaper binder for harvest
S_4 - hand weeding at 30 DAS + manual harvest

weeding with manual harvest (S_4). The treatment involving Quizalofop ethyl application with manual harvesting (S_2) showed the lowest energy productivity. Comparable to hand weeding, the application of Quizalofop ethyl controlled the weeds inadequately resulted in lower seed yield and thus reflected in lower energy productivity. Energy productivity showed a strong positive correlation with seed yield (Fig. 2). A reduction in seed yield leads to a corresponding decline in energy productivity. These results are consistent with the past findings (34) which emphasized the importance of proper weed management in achieving optimal energy productivity in Black gram.

Regarding energy intensiveness, an inverse trend was observed compared to energy productivity. The lower energy intensiveness was recorded in line sowing (M_4) with values of 0.2171, 0.2189 and 0.2149 MJ/₹across the three seasons. Among the mechanical planting methods, all treatments (M_1, M_2 and M_3) showed relatively higher energy intensiveness, ranging from 0.2417 to 0.2567 MJ/₹ during the summer of 2023. The other two seasons exhibited similar patterns. Production cost is the important factor that is inversely proportional to energy intensiveness, lower energy input and production cost in machinery result in lower energy intensiveness. Lower energy intensiveness due to high energy input and cost of cultivation in sesame, supporting the present studies (31).

To weed management and harvesting methods, hand weeding with manual harvesting (S_4) demonstrated lower energy intensiveness (0.2040, 0.2055 and 0.2023 MJ/₹) across seasons, followed by reaper binder harvesting with hand weeding (S_3). The higher energy intensiveness was observed in the S_1 treatment, ranging from 0.2682 to 0.2775 MJ/₹ across seasons. This variation could be attributed to differences in input energy requirements and associated costs for different weed management and harvesting methods. Similar results were reported earlier (34), in weeding operations, the usage of chemicals resulted in higher energy intensiveness in Black gram. The energy intensiveness was significantly negatively correlated with energy input and cost of cultivation (Fig. 2). The energy input and cost of cultivation were inversely proportional to energy intensiveness, with higher values of these variables resulting in lower energy intensiveness.

The interaction between main plot (crop establishment methods) and sub-plot treatments (weed management and harvesting methods) was found to be non-significant for both energy productivity and energy intensiveness parameters.

Energy intensity in physical and economic terms

The analysis of energy intensity parameters presented in Table 7 revealed significant differences across various treatments in sesame cultivation over three seasons.

Energy intensity in physical terms

With regards to planting methods, the energy intensity in physical terms was recorded significantly higher with a pneumatic precision planter without pelletized seeds (M_3), showing values of 4.314, 5.055 and 3.798 MJ/kg) during summer 2023, kharif 2023 and summer 2024, respectively. This higher energy intensity can be attributed to the inefficiency in seed placement and crop establishment, leading to suboptimal plant growth and reduced yield. On the other hand, line sowing (M_4) consistently recorded lower energy intensity values (3.485, 4.000 and 3.134 MJ/kg), reflecting more efficient energy utilization in producing sesame yields, likely due to better seed placement and crop establishment, which enhances overall plant vigor and yield efficiency. This trend indicates that conventional line sowing required less energy input per unit of biological yield compared to mechanized planting methods, particularly those utilizing non-pelletized seeds. These findings align with the past studies (35) wherein, simpler planting methods often demonstrate better energy use efficiency in corn. The variable energy intensity in physical terms had negatively correlated with biological yield (Fig. 2). Thus, increased biological yield results in lower energy intensity.

In weed management and harvesting methods, the higher energy intensity was recorded in Quizalofop ethyl application with manual harvesting (S_2), ranging from 3.605

Table 7. Effect of different crop establishment techniques, weed management and harvesting methods on energy intensity of sesame

Treatments	Energy intensity in physical terms (MJ/kg)			Energy intensity in economic terms (MJ/₹)		
	summer 2023	kharif 2023	summer 2024	summer 2023	kharif 2023	summer 2024
Main plots (M)						
M_1	3.692	4.248	3.288	0.3946	0.3835	0.4210
M_2	4.009	4.663	3.557	0.3572	0.3437	0.3823
M_3	4.314	5.055	3.798	0.3344	0.3201	0.3590
M_4	3.485	4.000	3.134	0.3677	0.3538	0.3924
S. Em. ±	0.068	0.087	0.063	0.0063	0.0060	0.0067
C.D. (P=0.05)	0.235	0.301	0.218	0.0217	0.0208	0.0232
Subplots (S)						
S_1	3.951	4.594	3.470	0.4118	0.4009	0.4421
S_2	4.063	4.746	3.605	0.3565	0.3467	0.3824
S_3	3.677	4.218	3.287	0.3668	0.3513	0.3909
S_4	3.809	4.408	3.415	0.3189	0.3022	0.3393
S. Em. ±	0.074	0.103	0.073	0.0076	0.0074	0.0082
C.D. (P=0.05)	0.217	0.300	0.213	0.0222	0.0215	0.0238

Interaction absent

Main plot: M_1 - Inclined plate planter using pelletized seeds
M_2 - Pneumatic precision planter using pelletized seeds
M_3 - Pneumatic precision planter using non-pelletized seeds

Subplot: S_1 - Quizalofop ethyl @ 50 g a.i./ha at 20 DAS + reaper binder for harvest
S_2 - Quizalofop ethyl @ 50 g a.i./ha at 20 DAS + manual harvesting,
S_3 - hand weeding at 30 DAS + reaper binder for harvest

to 4.746 MJ/kg across seasons, which was on par with S_1 (Quizalofop ethyl + reaper binder). Hand weeding at 30 DAS with reaper binder harvesting (S_3) reported the lower energy intensity in physical terms across seasons, followed by manual harvesting (S_4). It suggests that more energy was required to produce each unit of sesame yield compared to other weed management and harvesting combinations. This can be attributed to the relatively less effective weed control by Quizalofop ethyl, leading to lower yield potential and increased energy consumption for weed management and harvesting. In contrast (S_3) demonstrated the lowest energy intensity, reflecting more efficient energy use per unit of output due to better weed control and timely harvesting. Manual harvesting (S_4) also resulted in relatively low energy intensity, though slightly higher than S3, likely due to the labour-intensive nature of manual harvesting. This trend could be attributed to the better weed control achieved through manual weeding, resulting in higher biological yield per unit of energy input. These results were well supported by previous reports (34), which reported the lower biological yield due to the application of post-emergence herbicide responsible for high energy intensity in physical terms.

Across all seasons, no interaction effect was observed on sesame's energy intensity in physical terms among the combinations of establishment methods, weed management strategies and harvesting techniques.

Energy intensity in economic terms

In crop establishment techniques, inclined plate planter with pelletized seeds (M_1) showed higher values (0.3946, 0.3835 and 0.4210 MJ/₹) over other methods. It can be attributed to the increased energy requirement for planting and the associated costs, particularly due to the additional energy needed for preparing and planting pelletized seeds. This method, while providing efficient seed placement, tends to be more energy-intensive, leading to higher values of energy intensiveness in economic terms. In contrast, the Pneumatic precision planter without pelletized seeds (M_3) recorded lower values during the three seasons. This is likely due to the reduced energy input required for the sowing process, as the absence of pelletized seeds eliminates the extra energy used for seed preparation, although this might result in lower planting efficiency and yields. This inverse relationship between physical and economic energy intensity could be attributed to variations in the cost of cultivation and energy output ratios resulting in higher values of energy intensity in inclined plate planters. The past findings stated that the best profitable crop establishment method, used machines, resulted in higher energy intensity (36).

Among weed management and harvesting methods, the application of Quizalofop ethyl at 20 DAS with reaper binder harvesting (S_1) recorded more values (0.4118, 0.4009 and 0.4421 MJ/₹) across all three seasons compared to other weed and harvesting strategies. Hand weeding with manual harvesting (S_4) consistently showed a lower economic energy intensity (0.3189, 0.3022 and 0.3393 MJ/₹) across seasons. The use of Quizalofop ethyl at 20 DAS involves additional energy consumption for herbicide application, while the reaper binder, although efficient, also requires significant fuel and labour inputs. This combination results in higher energy costs per unit of output, leading to higher values of economic energy intensity. In contrast, the hand weeding and manual harvesting method (S_4) consistently demonstrated lower economic energy intensity. This can be explained by the reduced reliance on external inputs such as herbicides and machinery. Although manual labour is more energy-intensive in terms of human effort, the absence of mechanical and chemical inputs reduces overall energy expenditure, resulting in lower energy intensity per unit of crop yield across seasons. This highlights the trade-off between mechanical efficiency and energy consumption in agronomic practices. This trend indicates that despite higher labour requirements, manual harvesting provided better economic returns per unit of energy output. The best profitable weed control measures of the use of herbicides resulted in higher energy intensity (34) in Black gram, which supported the present study. The variable energy intensity in economic terms negatively correlated with cost of cultivation (Fig. 2). It shows that a lower cost of cultivation resulted in higher energy intensity in economic terms.

Energy intensity in economic terms was a non-significant interaction effect between crop establishment methods (main plot) and weed management and harvesting methods (sub-plot treatments).

Conclusion

Over the three-season investigation, significant differences were observed in sesame seed and biological yields, as well as energy parameters, influenced by crop establishment techniques, weed control methods and harvesting practices. Manual line sowing of sesame consistently achieved higher performance across several metrics, including seed and biomass yields, cultivation costs and energy-related parameters such as energy output, energy ratio, net energy gain, energy balance/unit input and energy productivity. Conversely, specific energy and energy intensity in physical terms were greater with the pneumatic precision planter used without pelletized seeds, while energy intensiveness and economic energy intensity were higher with the inclined plate planter using pelletized seeds. In terms of weed control and harvesting methods, the combination of hand weeding with either reaper binder or manual harvesting (S_3 and S_4 treatments) showed superior results in seed and biomass yields, cultivation costs and energy efficiency parameters like energy input, energy output, energy ratio, net energy gain, energy balance/unit input and energy productivity. However, specific energy, physical energy intensity and energy intensiveness were higher in the treatment using Quizalofop ethyl combined with manual harvesting. Additionally, Quizalofop ethyl paired with reaper binder harvesting exhibited a higher economic energy intensity. Therefore, the field experiment validates that line-sown sesame, paired with hand weeding and reaper binder harvesting, resulted in superior seed and biological yields and energy efficiency. Based on the study, future recommendations include optimizing mechanized sowing methods to improve seed placement and yield, integrating chemical and manual weed control for enhanced efficiency and promoting the adoption of energy-efficient practices like line-sowing and reaper binder harvesting through farmer training and subsidies.

Additionally, expanding research on renewable energy use and long-term environmental impacts can further improve sustainability. Scaling these practices to other sesame varieties and regions will validate broader applicability.

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Authors' contributions

MP carried out the field experiment and data analysis and prepared the manuscript. NT guided for experimenting, corrected the manuscript and provided assistance. CH monitored the experiment and assisted. RU provided necessary guidance on pelletization and sowing techniques. RK provided the necessary machinery and guidance for experimenting. MB made corrections to the manuscript. RB monitored the experiment. SR and TR helped in editing, summarizing and revising the manuscript.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical issues: None

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